ISOGAL survey of Baade's Windows

Ian S. Glass[1], D.R. Alves[2], and the ISOGAL and MACHO teams

[1] S.A. Astronomical Observatory, PO Box 9, Observatory 7935, South Africa
[2] Space Telescope Science Institute, Baltimore, MD 21218, USA

Abstract. The Baade's Windows of low obscuration towards the inner parts of the Galactic bulge represent ideal places in which to develop an understanding of the ISOGAL colour-magnitude diagrams. Unlike the case for the solar neighbourhood, their contents are at a uniform distance from the Sun, affected only by the finite thickness of the Bulge.

The objects detected in the ISOGAL survey are found to be late-type M-giants at the red giant tip or on the Asymptotic Giant Branch (AGB). The ISOGAL colour-magnitude diagrams show that mass-loss starts at about M4 and increases towards later types. Many non-Miras have mass-loss rates similar to shorter-period Miras.

The visible counterparts of the ISOGAL sources have been identified in the database of the MACHO gravitational lensing survey. A first report of this work is included here. It is found that nearly all the ISOGAL sources are semi-regular variables (SRVs), which are many times more numerous than Miras. Their stellar luminosities increase with period. Based on a simple interpretation of the photometry, mass-loss rates from about 10^{-9} $M_\odot$ yr^{-1} to 10^{-7} $M_\odot$ yr^{-1} are found for SRVs with periods in excess of $\sim$60 days.

1 Introduction

The ISOGAL survey (see Omont, this volume) has covered a large number of heavily obscured fields in the inner galaxy in the mid-infrared, using the ISOCAM filters LW2 (5.5–8 μm) and LW3 (12–18 μm). Very little information is available concerning individual stars in most of the survey areas and it was decided to include the relatively well-studied Baade's Windows (BW) of low obscuration, namely NGC 6522 ($l=+1°$, $b=-3.8°$) and Sgr I ($l=1.37°$, $b=-2.63°$), whose A_V is about 1.5, for comparison purposes. The M-type stellar content of the NGC 6522 field has been surveyed by Blanco, McCarthy and Blanco (1984) and Blanco (1986). Frogel & Whitford (1987) have presented near-IR photometry of many stars. The census of Mira (V amplitude > 2.5 mag) variables in these fields is complete and their periods have been found by Lloyd Evans (1976, photographic infrared) and Glass et al. (1995, *JHKL* region). The K and bolometric magnitudes of the Miras obey period-luminosity relations. No carbon-type AGB stars have been found in these fields.

The results of the ISOGAL BW survey have recently been presented by Glass, Ganesh et al. (1999). In the two ISOGAL fields, each of 15 × 15

arcmin^2, a total of 1,193 objects were found. The survey is believed to be complete to a level of 5 mJy in both bands, corresponding to [7] = 10.64 and [15] = 8.99 mag. The photometric errors are < 0.2 mag for bright sources, rising to < 0.4 mag for faint ones. The sensitivity and spatial resolution of ISOCAM are about two orders of magnitude better than with IRAS. At the faint end, the density of sources approaches the confusion limit.

The principal conclusions of the survey are illustrated by Fig. 1. There is a continuous sequence of increasing [15] mag with [7] – [15] colour. Much of the scatter is due to the distribution in depth of the Bulge, as found for the Mira log $P - K$ relation ($\sigma = 0.35$; see Glass et al., 1995). Making use of the known spectral types of many objects, the data are interpreted as evidence for increasing dust emission with increase of stellar luminosity and decrease of temperature. Substantial numbers of stars in these fields have luminosities and mass-loss rates similar to those of the shorter-period Miras.
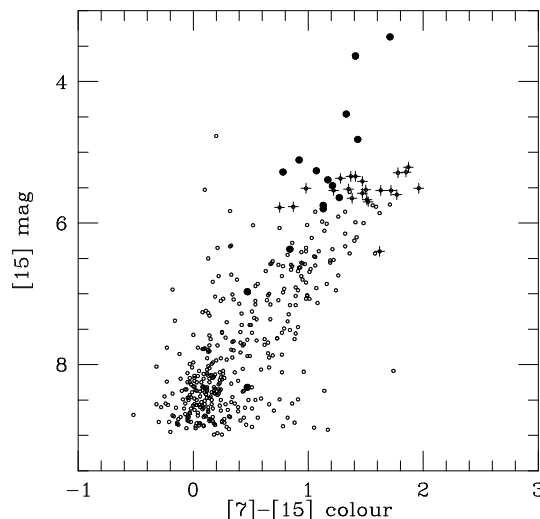

Fig. 1. ISOGAL colour-magnitude diagram for sources detected in the NGC 6522 and Sgr I Baade's Windows. A sequence of increasing 15 μm flux (flux arising in part from dust emission) with [7]–[15] colour (i.e., dust relative to photosphere), starts at the tip of the RGB in the bottom left corner and ends with the Miras at top right (solid points). Many other stars in the diagram, such as those with crosses, have luminosities and mass-loss rates similar to the shorter-period Miras. There is some contamination from foreground stars with small [7] - [15] colour.

The ISOGAL 7 μm flux of a late-type star with an optically thin dust shell arises from its photosphere, while the 15 μm flux arises from a combination of the photosphere and the dust. This is illustrated in Fig. 2, an opacity-sampled stellar atmosphere calculation including "astronomical silicate" dust, taken from Aringer et al. (1999). The bandpasses of the ISOCAM LW2 and LW3

filters are superimposed. It will be noticed that the $7\,\mu$m band is hardly affected by dust emission, but exhibits absorption features, probably due to water vapour and SiO. The 15μm band, on the other hand, may be dominated by silicate emission, which can greatly exceed that from the photosphere in this region.
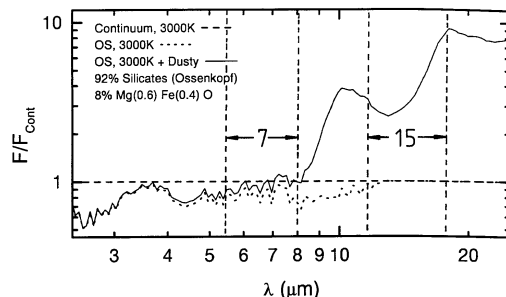

Fig. 2. Model of a 3000K stellar atmosphere with an "astronomical silicate" dust shell, taken from Aringer et al (1999), with ISOCAM filter limits marked. The fluxes have been normalized to a 3000 K blackbody. Note that the 7μm ISOGAL filter mainly measures a photospheric flux, while the 15μm filter is mainly sensitive to dust.

2   Correlation with MACHO

The Baade's Windows fields form part of the Bulge area that was surveyed nightly for six seasons of ~ 250 days by the MACHO gravitational lensing project. The MACHO observations were made in two bands, v and r, at effective wavelengths around 500 nm and 700 nm, and were transformed using formulae from Alcock et al. (1999) to Kron-Cousins V, R. The completeness and sensitivity to small-amplitude variations of MACHO and similar CCD-based surveys is much greater than in all previous work which depended on photographic techniques. In particular, large numbers of small-amplitude SRVs in the solar neighbourhood might be found if data of MACHO quality were available.

Counterparts of the ISOGAL sources were sought within a radius of 3 arcsec of their nominal positions. Since it is known that the ISOGAL sources are red giants, or else very bright early-type stars, only MACHO stars with $V < 13.5 + 4.67(V-R)$ were considered as candidates, with $(V-R)$ taken to be 0.5 in cases where only one colour was available. This left 40,000 objects in the two fields to select from. There were 904 positional matches. The distributions of distance residuals for the two fields, together with, as a test, random matches produced when the MACHO star coordinates were displaced by 15 arcsec, show that spurious matches should not exceed about 10% in

NGC 6522 and about 20% in Sgr I, which is a denser field. Sources which were not matched fell on gaps in the MACHO detector mosaic or, in a few cases, were too bright to be included in the MACHO database. A total of 332 stars had photometry at V, R, $7\,\mu$m and $15\,\mu$m and these were analysed further.

3   Periods and light curves

Almost all the 332 selected counterparts show variability at some level, and may be classified as semi-regular variables. Twenty-eight stars, most of them foreground bright objects, were rejected for saturation effects in their MA-CHO lightcurves (these included two Miras). Five of the ∼14 known Miras in the ISOGAL fields (see Glass, Ganesh et al., 1999) were recovered; the remaining 7 had already been rejected at the matching stage. Fourier amplitude spectra were calculated for all 332 members of the sample. In general, a short period (15 to 200 days) could be identified, but, for many sources, slower variability, not necessarily periodic, was also evident. Because of the seasonality of the data, each season was also analysed separately and the Fourier amplitude spectra were summed before searching for the most significant periods. Work is continuing on the period-finding, which may still be subject to revision.
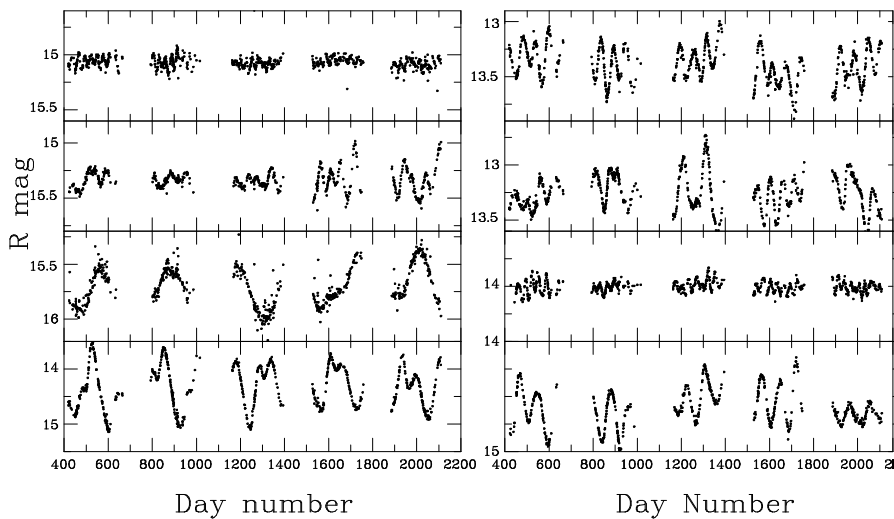

Fig. 3. Sample MACHO light curves of SRVs.

The light curves (see Fig. 3) and periods are similar to those found by Wood et al (1999) for AGB stars in the Large Magellanic Cloud. As in the LMC, the SRVs outnumber the Miras by a large factor (∼ 20 in this case). However, although most SRV light curves show clear evidence for variability
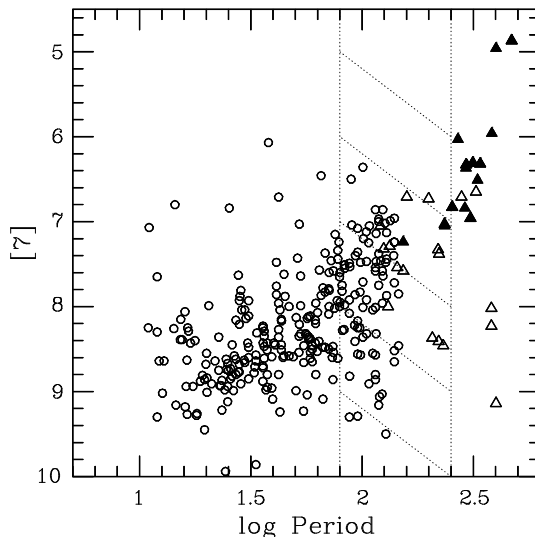
Fig. 4. Log P, [7] plot for cross-identified objects. The open points are the main periods identified. Open triangles are separately identified long periods and solid triangles are Mira (large-amplitude) variables, some of which were saturated in the MACHO data. Periods for these cases were taken from Glass et al. (1995). The periods in the hatched area may be subject to some revision.

in the 15–200 day range, as stated, only a few also show the longer periods around 300–400 days that seem to be common in the LMC (Type D in Fig. 2 of Wood et al. 1999).

In the log P, [7] diagram (Fig. 4), a clear period-luminosity correlation is seen for the SRVs (periods below $\log P = 2.2$) with a steeper slope for the Miras. The stars with periods longer than 200 days include the Miras, which do not show simultaneous shorter periods. One star shows a single period of around 300 days and a 7μm luminosity appropriate to a Mira, but is not a Mira. The group of three stars around $\log P = 2.35$ and [7] = 8.4 show no evidence for short periods. On the other hand, there are three low points with $\log P \sim 2.6$ which clearly show other periods around 50–60 days, allowing them alternative locations in the more heavily populated part of the diagram.

There is no clear period clumping among the SRVs. Instead, there seems to be a continuous progression, apart from the change in slope, in stellar luminosity, from the shortest period SRVs to the Miras. Solar neighbourhood SRVs with periods in the range 100-140 days show Population I kinematics that are similar to those of Miras with $P > 300$ days (Feast, 1963), although shorter-period Miras fall into population II. Also, s-process elements are sometimes detected in both these sets of stars (Little, Little-Marenin &

Bauer, 1987). This has led to suggestions that at least some of the SRVs are related to the long-period Miras, but pulsating in higher overtones.

3.1   Amplitudes and SRV classifications

The amplitudes of most of the SRVs are below 0.5 mag at R. The five Miras with MACHO light curves have amplitudes in the range 2.5–4. A few of the SRVs in the range 150–200 days have amplitudes of about 1 mag.

About two thirds of the light curves show persistent periodicity without much change in amplitude and could be classified SRa. The remainder, although they usually show persistent periodicity, also show slow random or very long-period level-shifts and are classified as SRb. However, it should be noted that these classsifications are subjective at best.

Kerschbaum & Hron (1992) classify O-rich SRVs as "blue" or "red", according to their $V - [12]$ and IRAS colours. Probably the blue SRVs correspond to those stars with $[15] \geq 8$ and $[7] - [15] \sim 0$, while the red SRVs are more luminous at 15μm and have dust emission (see below).

4   Mass loss

For an order-of-magnitude estimate of the mass loss associated with a given star, we can estimate its $15\,\mu$m flux excess due to dust emission by assuming that the photospheric flux can be extrapolated as a Rayleigh-Jeans tail from the $7\,\mu$m measurement, which should be almost entirely free of dust emission. The result is shown in Fig. 5.

The mass-loss rates for the SRVs overlap those of the shorter-period Miras and clearly do not depend on amplitude of pulsation. The lack of measurable mass-loss for stars with $P < 60$ days accords with the finding of Kerschbaum, Oloffson & Hron (1996) that mass-loss from stars having $0 < P < 75$ days could not be detected in CO radio emission, while those in the range $75 < P < 175$ days had a 50% detection rate.

Jura (1987) gives for the mass-loss from an AGB star:

$$\dot{M} = 1.7 \times 10^{-7} v_{15} R_{kpc}^2 L_4^{-1/2} F_{\nu,60} \lambda_{10}^{1/2} M_\odot \mathrm{yr}^{-1},$$

where v_{15} is the gas outflow velocity in units of 15 kms^{-1}, determined from CO observations, R is the distance to the star in kpc, L_4 is the stellar luminosity in units of $10^4\ L_\odot$, $F_{\nu,60}$ is the flux from the object at $60\,\mu$m and λ_{10} is the mean wavelength of light emerging from the star in units of $10\,\mu$m. We take v to be 8 km sec^{-1}, the average value determined for semi-regular variables by Kerschbaum, Olofsson & Hron (1996), $R \sim 8.2$ kpc, and $L_4 = 0.3$, from the bolometric magnitude of a 200-day Mira (Glass et al. 1995). To relate the given $15\,\mu$m flux to the $60\,\mu$ flux required, we very tentatively take the relation by Jura (1986), intended for carbon stars (but see also the

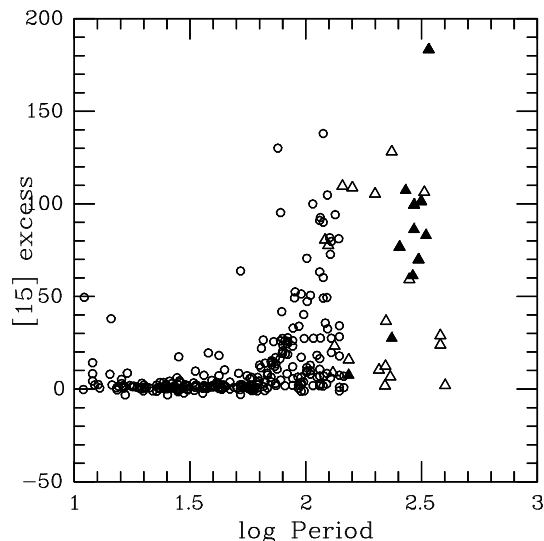**Fig. 5.** Excess 15μm fluxes in mJy, beyond what is expected by assuming a Rayleigh-Jeans photospheric energy distribution fitted to the 7μm fluxes, shown plotted against log period. Having a period $P > 60$ days seems to be a necessary, but not a sufficient, condition for significant mass-loss.

values of Q_{abs} for astronomical silicate grains; Draine & Lee, 1984), namely $F_\nu \propto \nu^{1.54}$. If the excess 15 μm flux is 100 mJy, we obtain $\dot{M} = 1.3 \times 10^{-7}$ $M_\odot$ yr^{-1}.

Figure 5 suggests that the lower rate limit of mass-loss that we detect is about two orders of magnitude less than the example discussed, or about 10^{-9} $M_\odot$ yr^{-1} (cf. Omont et al., 1999).

Mass-loss in SRVs is apparently a function of T, L and P. Because high luminosity in LPVs is also associated with low temperatures, it is unclear how these quantities separately affect $\dot{M}$. Considering L as an independent variable, from Fig. 6 we see that mass-loss increases with luminosity according to the approximate relation

$$\dot{M} \propto L^{2.6},$$

where we have assumed that $\dot{M}$ is proportional to the 15 μm flux excess and the bolometric luminosity of the star is proportional to the 7 μm flux (note that in the case of Miras dust emission may also contribute to the 7 μm band, leading to an over-estimate of photospheric luminosity).

Finally, the reader interested in the general properties of SRVs should remember that we have discussed so far only those stars which were detected in both MACHO and both ISOGAL bands. A preliminary glance at the light curves of the stars seen by ISOGAL only at 7 μm indicates that most of them are also SRVs, but presumably with mass-loss rates too low for 15 μm detection.
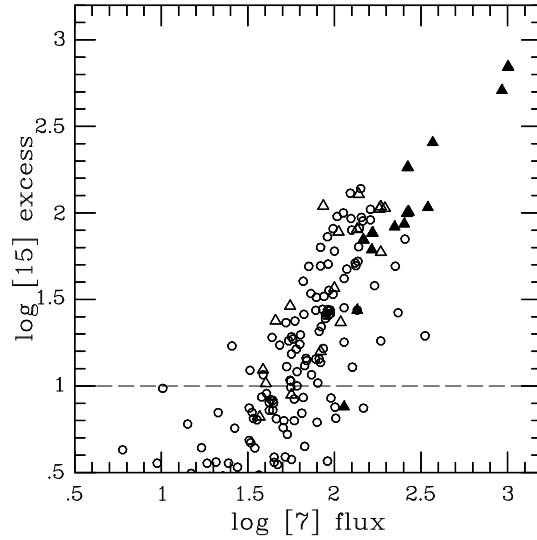
Fig. 6. Log [15] excess, an indication of mass-loss, vs log [7] flux, an indication of bolometric mag. Below the dashed line the data may be subject to photometric errors, exaggerated by taking logarithms. The slope is about 2.6.

References

1. Alcock C. et al (MACHO collaboration), 1999, PASP (in press)
2. Aringer B., Kerschbaum F., Hron J., Posch T., Windsteig W., Jorgensen U.G., Höfner S., 1999 In IAU Symp 191, Asymptotic Giant Branch Stars, ed Le Bertre T., Lèbre A., Waelkens C., Astronomical Society of the Pacific, San Franscisco
3. Blanco V.M., 1986, AJ, 91, 290
4. Blanco V.M., McCarthy M.F., Blanco B.M., 1984, AJ 89, 636
5. Draine B.T., Lee H.M., 1984 ApJ, 285, 89
6. Feast M.W., 1963, MNRAS, 125, 367
7. Frogel J.A., Whitford A.E., 1987, ApJ, 320, 199
8. Glass I.S., Whitelock P.A., Catchpole R.M., Feast M.W., 1995 MNRAS, 273, 383
9. Glass I.S., Ganesh S., Alard C., Blommaert J.A.D.L., Gilmore G., Lloyd Evans T., Omont A., Schultheis M. and Simon G., 1999, MNRAS 306, 127
10. Jura M., 1986, ApJ, 303, 327
11. Jura M., 1987, ApJ, 313, 743
12. Kerschbaum F., Olofsson H., Hron J., 1996, A&A, 311, 273
13. Kerschbaum F., Hron J., 1992, A&A, 263, 97
14. Little S.J., Little-Marenin I.R., Bauer W.H., 1987, AJ, 97, 981
15. Lloyd Evans T., 1976, MNRAS, 174, 169
16. Omont A. et al., 1999, A&A, 348, 755
17. Wood P.R. et al (MACHO collaboration) 1999 In IAU Symp 191, Asymptotic Giant Branch Stars, ed Le Bertre T., Lèbre A., Waelkens C., Astronomical Society of the Pacific, San Franscisco